Critical evaluation on structural stiffness of porous cellular structure of cobalt chromium alloy

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Critical evaluation on structural stiffness of porous cellular structure of cobalt chromium alloy

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Abstract. In order to improve the stiffness characteristics of orthopedic devices implants that mimic the mechanical behavior of bone need to be considered. With the capability of Additive layer manufacturing processes to produce orthopedic implants with tailored mechanical properties are needed. This paper discusses finite element (FE) analysis and mechanical characterization of porous medical grade cobalt chromium (CoCr) alloy in cubical structures with volume based porosity ranging between 60% to 80% produced using direct metal laser sintering (DMLS) process. ANSYS 14.0 FE modelling software was used to predict the effective elastic modulus of the samples and comparisons were made with the experimental data. The effective mechanical properties of porous samples that were determined by uniaxial compression testing show exponential decreasing trend with the increase in porosity. Finite element model shows good agreement with experimentally obtained stress-strain curve in the elastic regions. The models prove that numerical analysis of actual prosthesis implant can be computed particularly in load bearing condition

1. Introduction

The major challenge in developing medical implant devices is to produce biocompatible alloys which possess good tensile and fatigue properties. The technique used to manufacture these alloy can markedly affect the mechanical and metallurgical properties of the resulting components [1]. Additive manufacturing (AM) was proposed as a novel candidate for the fabrication of customized biomedical implants with the cobalt alloys. Among them, is direct metal laser sintering (DMLS) which has been a high demand since it offers a lower time-to-market, a near-net-shape production, a higher material utilization rate, along with its ability to produce functional metallic parts with mechanical properties comparable to those in bulk materials [2]. From the previous studies, SLM has the potential of controlling porosities according to the capacity of providing different energy inputs by its processing parameters while in DMLS process all the parameters were constant. A study on cobalt chromium molybdenum (CoCrMo) powder using DMLS shown that minor porosity produced by the highest layer thickness, which provided a better particle packing. Thus thermal conductivity among the particles was enhanced and subsequently permitted successful densification, and finally removed or shrunk pores.

Cobalt (Co) in CoCrMo alloys exhibits high corrosion resistance and has excellent wear resistance which makes Co, often employed as artificial joints and body implants. Co also shows stability of allotropic transformation at room and elevated temperatures. In biomedical applications, CoCrMo alloys (ASTM F75) were much preferred to be used in human since they are free of Nickel (Ni). Ni element is well known as highly toxic element [3].

Finite element analysis (FEA) can be used to identify a suitable replacement for conventional materials and designs through practical applications in self-programmed and commercial simulation software, using e.g. MATLAB, COMSOL, ABAQUS or ANSYS. FEA method is common in the biomechanical study to predict implant performance. Prediction of macroscopic mechanical properties of porous structures using (FEA) can reduce amount of experimental works needed in tailoring special properties of porous implants hence allows researchers to predict stress distribution in the contact area of the implants with the bones by solving structural mechanics problems using numerical approximation [4]. Recent study shows that the effective elastic modulus of porous structure of CoCr biomedical grade alloy produced by selective laser melting (SLM) can be predicted using FEA [5] to some extent. However, the discrepancies in result for a wide range of porosities are still huge as compared to experiment due to heterogeneity structure resulted from rapid melting and cooling of SLM process [6].

In this study, focuses on applying the method of direct metal laser sintering (DMLS) process to CoCrMo which expected have a capability as an orthopaedic implant with tailored mechanical properties. This research combines the simulation n and experimental method in result to find out the stiffness of the samples. Therefore, it can meet up effectively to predict the mechanical properties by computing analysis.

2. Methodology

2.1. Component design

CAD models individual open cellular structures were generated using Solidworks 2013 software. The porosity of cellular structure determined using equation (1). Wall thickness of open cellular structures samples were fixed at 0.80 mm with pore sizes in square shape ranging between 0.60 and 1.80 mm within 15 mm cubic. Detailed of individual CAD models are shown in figure 1(a). In this design, only porosity volumes were designed at 60%, 70% and 80%.

$$\text{Porosity}, \varphi = \frac{V_p}{V_b} \tag{1}$$

Where

Vp = Volume of pores

Vb = Volume of bulk

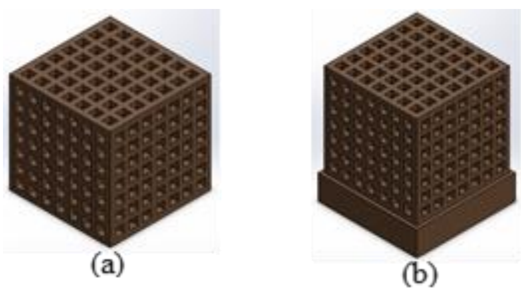

Figure 1. CAD model (a) individual and (b) extension basement.

The solid models were exported from the CAD software in STL file format into Materialise Magics 17.0 software. The components were then positioned on the build platform and slice files were generated to enable manufacture. A typical CAD model of the component shows extension basement to ease detachment on completing fabrication as show in figure 1(b).

2.2. Component design
In this study, the actual structures were produced by EOSINT M280 Direct Metal Laser Sintering machine using metal powder from EOS Cobalt Chrome MP1 which is a Cobalt Chromium Molybdenum, CoCrMo powder super alloy biomaterial. Parts build from EOS Cobalt Chrome MP1 complied with the chemical composition of UNS R31538 of high carbon CoCrMo alloy as shown in table 1. The alloy is nickel-free (< 0.1 % nickel content) and was characterized for fine, uniform crystal grain structure. As built EOS Cobalt Chrome MP1 meets the chemical and mechanical specifications of ISO 5832-4 and ASTM F75 for cast CoCrMo implant alloys, and the specifications of ISO 5832-12 and ASTM F1537 for wrought CoCrMo implants alloys except remaining elongation. Ideally, elastic modulus, Poisson's ratio and full density of a stress relieved EOS Cobalt Chrome MP1 were given as 200 GPa, 0.3 mm and 8.3 g/ cm3, respectively.

Table 1. Physical and composition of EOS Cobalt Chrome MP1 (CoCrMo) [7].

Material composition (wt-%)	Co(60-65) Cr(26-30) Mo(5-7) Si(≤1.0) Mn(≤1.0) Fe(≤0.75) C(≤0.16) Ni((≤0.10)
Relative density (%)	Approximately 100
Density (g/cm^3)	Approximately 8.3

2.3. Sample manufacturing
The structures made from EOS EOS Cobalt Chrome MP1 powder was filled up and sieved to a particle size of no greater than 25µm into dispenser platform and the components were manufactured using the DLMS EOSINT M280 Direct Metal Laser Melting machine. A schematic diagram of SLM process is illustrated in figure 2(a). The machine uses laser system with spot diameter of 100µm to selectively melt the powder. The components were built using 20µm layers. The parameters were; laser power of 195W, laser step over distance of 0.08 mm and a laser scan speed of 800 mm/s. The fabrication chamber was filled up with argon gas with less than 1.3 % oxygen present. All completed samples were then detached from the substrate using electro discharge machining (EDM) wire-cut prior to geometrical measurement.

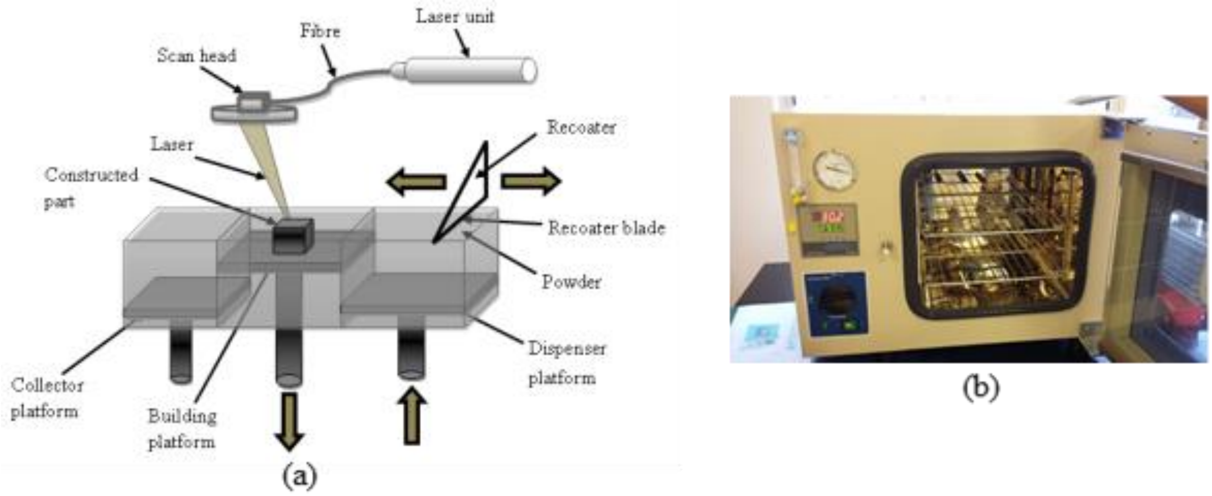

Figure 2. (a) Schematic diagram of SLM and (b) Stress relieve process.

2.4. Correlation of published empirical equation

In order to obtain an additional comparison with the physical test results and numerical analysis, a model proposed in [4, 6] were utilized. According to Gibson and Ashby, equation can be rewritten to calculate the effective elastic modulus as follows:

$$E_{eff} = E_s(1-\varphi)^2 \tag{2}$$

for Hazlehurst, Wang and Stanford, as in equation (3) where:

$$E_{eff} = E_s(1-\varphi)e^{(-2.376\varphi)} \tag{3}$$

Where;
E*s* is the elastic modulus of the solid CoCrMo alloy taken as 200 GPa and
φ is the porosity.

2.5. Finite element analysis

ANSYS Workbench 14.0 finite element modelling software was used to predict the effective elastic modulus of the individual structures and comparisons were made with the physical test data and analytical predictions. The software was also used to perform a simulation that considered the effect of structural variation and heterogeneities within a cellular structure, in order to investigate what effect this had on the effective stiffness. Three dimensional models created in Solidworks® 2013 that had been used for specimen manufacturing by SLM were transferred into ANSYS Workbench 14.0 environment for structural simulation. Linear static structural analysis was chosen to solve the static problem in order to obtain equivalent stress, equivalent strain and compressive deformation of each model within the set boundary conditions.

The full simulations with different load conditions were carried out using ANSYS DesignXplorer for obtaining mean stress-strain relationship of every sample with different porosity. Triangular meshes with minimum mesh size of 0.2mm are set for the FEA. Figure 3 shows that all meshes are together connected and all the struts and pores are defined as one geometry in a three dimensional model with the assumptions that all struts have identical size and the model is homogenous.

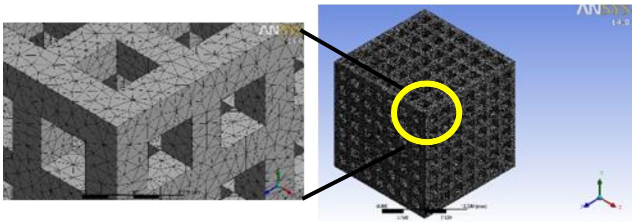

Figure 3. Mesh elements are together connected within the struts and pores with minimum mesh size of 0.2 mm of tetrahedral meshes.

In Static Structural Analysis function, the model was fixed at the bottom surface and a downward force was applied on the top surface as depicted in figure 4(a). Compression test on cellular structure were modelled for different porosity of unit cells in simulation prior to fabrication on the DMLS machine. Upon the convergence, three output variables were recorded, i.e. equivalent stress, equivalent strain and total deformation in Z-direction. The applied force increased for every load cycle until 1 mm structure deformation was achieved.

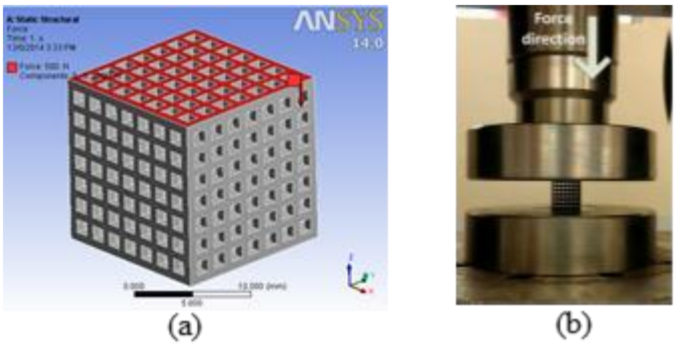

Figure 4. Load applied (a) FEA and (b) Experiment.

2.6. Compression test

Uniaxial compression tests were performed using a Shimadzu materials testing machine with a maximum load capacity of 100kN. Tests were performed to physically determine the compressive properties of the cellular structures in the orientation which they were built. The open cell specimens were elastic tested at stroke rate of 0.5 mm/min and the acquired real time mechanical testing data were recorded in a PC for further analysis (in accordance with IS0 13314:2011) with efforts being made to ensure uniaxial loading by using a machined fixture as shown in figure 4(b). The components were loaded to failure or until the maximum load capacity of the machine was reached. The stress strain relationship for each individual component was calculated from the real time force versus displacement data obtained from the test machine.

3. Results and Discussion

The specimens chosen are in cubic shape with controlled variations of porosity and strut size. The detail samples specification shown in table 2.

Table 2. Samples specification of 60%-80% porosity.

Sample	Cube size (mm x mm x mm)	Porosity (%)	Strut size (mm)	Pore size (mm x mm)
Sample 1	15x15x15	60	0.80	1.22x1.22
Sample 2	15x15x15	70	0.77	1.59x1.59
Sample 3	15x15x15	80	0.52	1.80x1.80

3.1. Samples fabrication

Open cellular structure CoCrMo alloy samples with various designed volume porosity have been successfully fabricated by DMLS process in this work. Sintered density of each sample attained higher than 7.96 g/cm3 that was 96 % of the theoretical density. Samples of different designed porosity are demonstrated in figure 5(a). An observation under optical microscope showed that there were structural variations found on external surfaces of each sample especially on the side (horizontal) faces. As shown in figure 5(b), the strut structures with irregular surfaces forfeited geometry integrity of the sample. This is different to ideal CAD design with smooth and uniform regular surface [7].

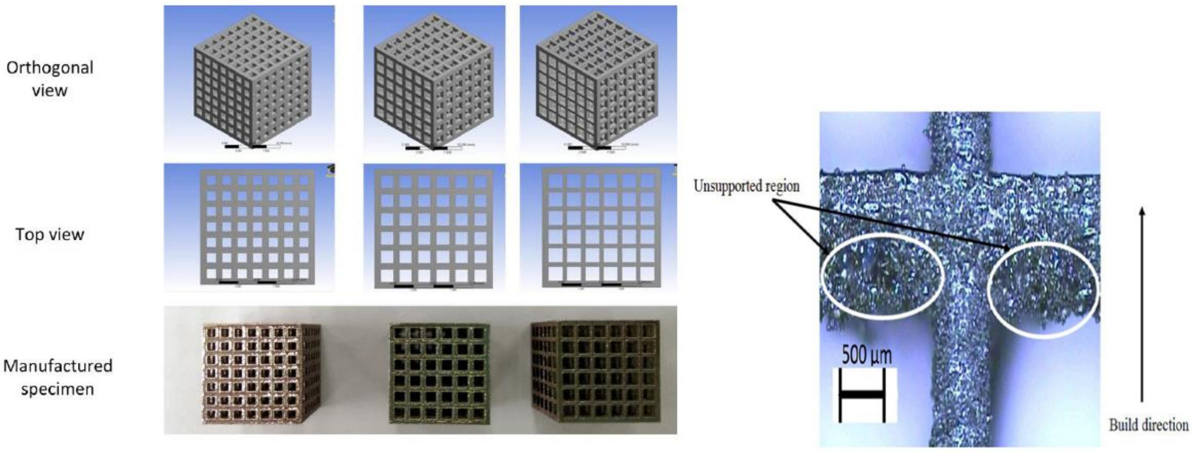

Figure 5. (a) Samples of different designed porosity and (b) Irregular surfaces.

3.2. Finite element analysis

In the FE Analysis, the representative volume element (RVE) method is selected to represent the porous structure of the implant and the mechanical properties, such as Total Deformation as on figure 6 (a). Equivalent Stress and Equivalent Static Strain are then calculated. Once the effective mechanical properties are determined for a range of structures and porosities, the value can then be the material input into the FEA analysis for assessing the performance of the final part. Periodic boundary conditions were assumed at all other faces. The RVE was meshed using tetrahedral elements. From the Equivalent Stress in finite element analysis, it show that stress concentration at the vertical strut and nearly the edge of pore area. Figure 6 (b) show the maximum stress concentration in RVE indicated by red colour area.

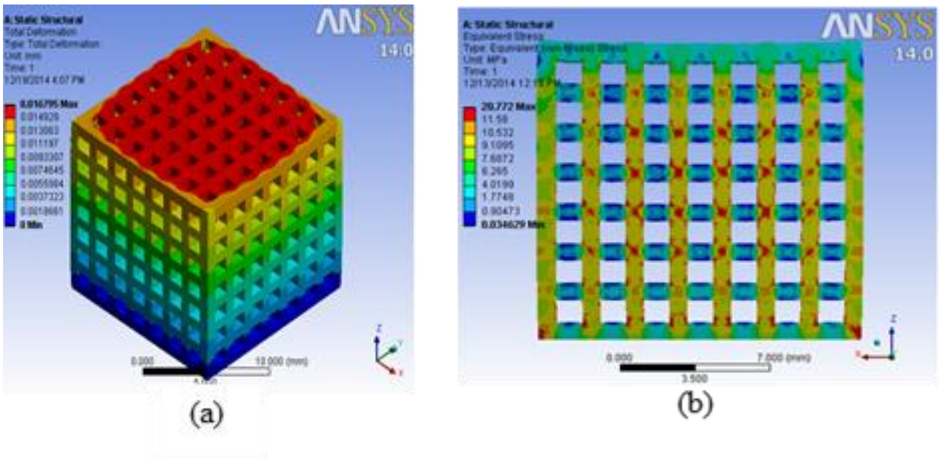

Figure 6. FEA contour plot for (a) total deformation and (b) maximum stress concentration.

The FEA was then used to predict the effective stiffness of the porous structure. The result obtained by FEA were used to draw relationships between stresses and strains of all cellular structures of different porosities using the applied forces and strokes obtained from the compressive test.

3.3. Experiment compression test
The experimental results reveal that the elastic modulus of open cell structure reduces tremendously as compared to solid material when produced by DMLS. Figure 7 shows the graph of compression test for the samples experienced 20 hours stress relieve process.

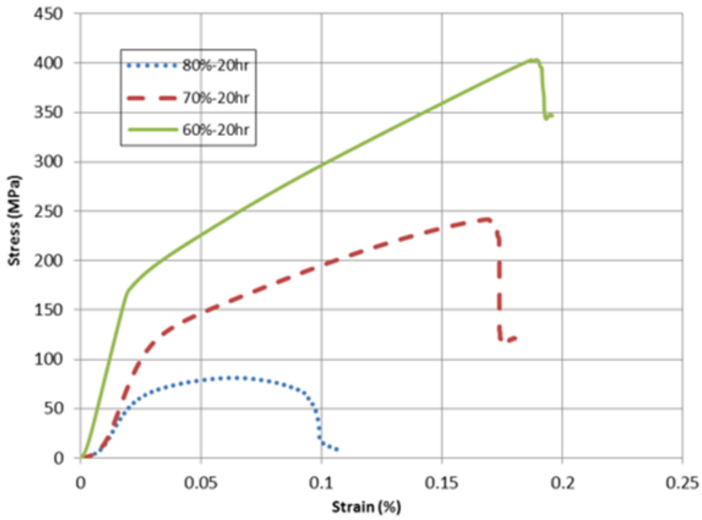

Figure 7. The graph for compression test.

3.4. Comparison FEA, experimental and published equation
The consideration to use the finite element method to predict the effective mechanical properties of cellular structures manufactured using DMLS. This would help to reduce the need for expensive and time consuming physical testing. The effective mechanical properties of cobalt chromium alloy cellular structures manufactured using DMLS with a rhombic dodecahedron unit cell in both uniaxial compression and flexure have been investigated and comparison have been carried out with the numerical results and the physical test data. Further tests considering the effective stiffness of Cobalt

chromium porous cellular structures, manufactured using DMLS with porosity ranging from 60% and 80%, were investigated when subject to finite element simulation and again the published data of empirical equations results significantly over estimated the stiffness. In this study, the focus is more to the linear region on the graph to obtain its effective elastic modulus as shown in figure 8. From the predicting effective stiffness value from simulation result graph, it shown that the close agreement of linear gradient in this work was achieved with the experimental results, showing the minimum different as show in table 3.

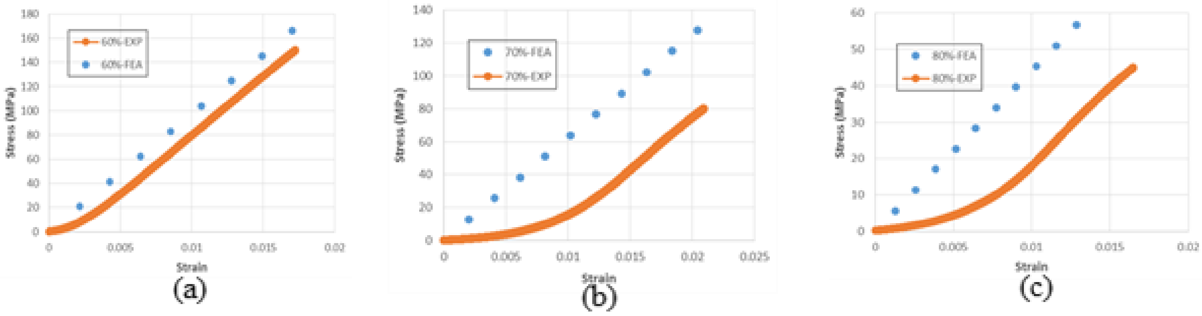

Figure 8. The linear region on the graph to obtain effective elastic modulus between FEA and experiment.

Table 3. Comparison result by simulation and experiment method.

Porosity (%)	Method	Elastic modulus (GPa)	Error
60	FEA	9.760	0.0085
	EXP	9.844	
70	FEA	6.260	0.0340
	EXP	6.481	
80	FEA	4.410	0.0640
	EXP	4.143	

The effective elastic modulus obtained in the experiment and simulation for different porosities was compared with the published correlations from [6] and modified Gibson [4]. It can be seen in Table 4 that the effective elastic modulus computed from the experiment are much lower than the published models. These might be due to the struts and pores sizes used in those models.

Table 4. Numerical and experiment effective elastic moduli comparison.

Porosity	Elastic modulus (GPa)			
%	FEA	EXP	Gibson Ashby	Hazlehurst et al.
0	200	200	200	200
60	9.76	9.844	32	19.23
70	6.26	6.481	18	11.27
80	4.41	4.143	8	5.98

The coefficient of determination R2 is another measure of how well the least squares equation performs as a predictor of stiffness. In this study, the relationship between the effective elastic modulus and porosity has been analysed using nonlinear regression due to the numerical and analytical results also showing non linearity. The derived expression has different coefficient of determination value (R2) based on the various method and the relationship can be observed from figure 9.

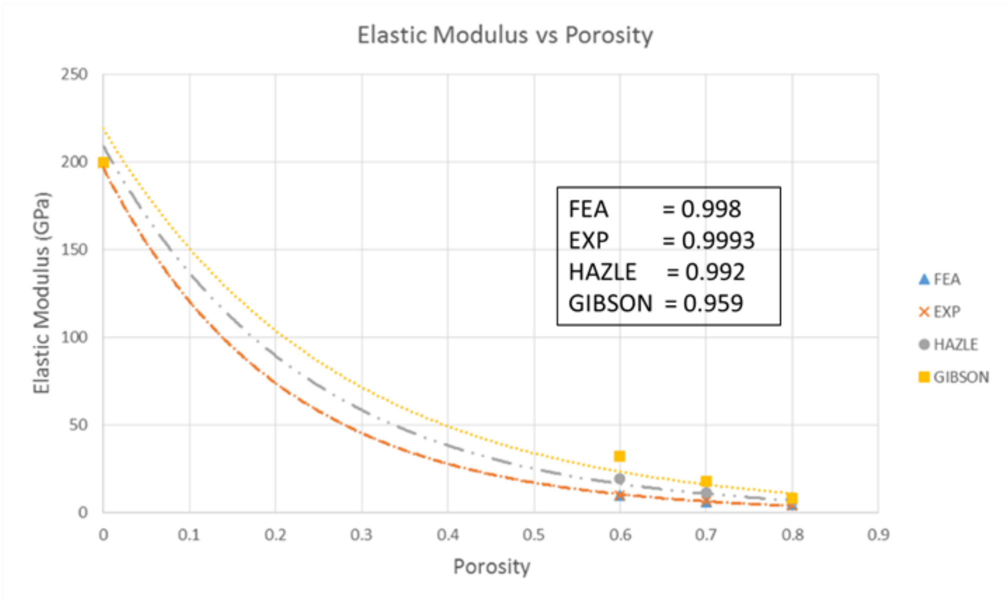

Figure 9. Different coefficient of determination values.

4. Conclusion

The development of Additive Layer Manufacturing (ALM) processes such as Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS) have introduced the capability to produce orthopaedic implants from common biomedical alloys, with tailored mechanical properties which can potentially emulate human bone and can be considered as viable alternative to manufacturing using traditional methods. This study evaluates the stiffness of the three different porosities (60%, 70% and 80%) of square pore CoCrMo cellular structures. These specimens are powder based and manufactured through DMLS processes particularly for orthopaedic applications. Influences of structural variation and heterogeneities on cellular structures stiffness are justified by using a finite element analysis. The analyses conducted in FEA are tally with the result produced in experiments. This include boundary conditions, mesh shapes and sizes and material properties in the function of sample porosities. The study contributes effective boundary conditions for advance simulation in predicting the stress distribution in real bone shape. The effective mechanical properties of porous samples that were determined by uniaxial compression testing show exponential decreasing trend with the increase in porosity. The models prove that numerical analysis of actual prosthesis implant can be computed particularly in load bearing condition.

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